Collimation studies with hollow electron beams

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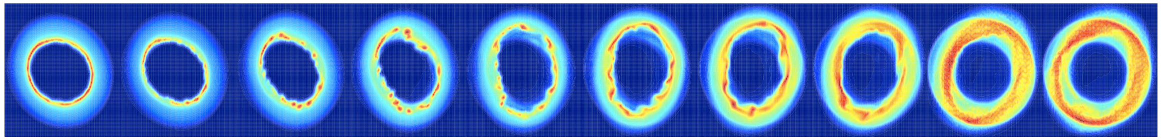
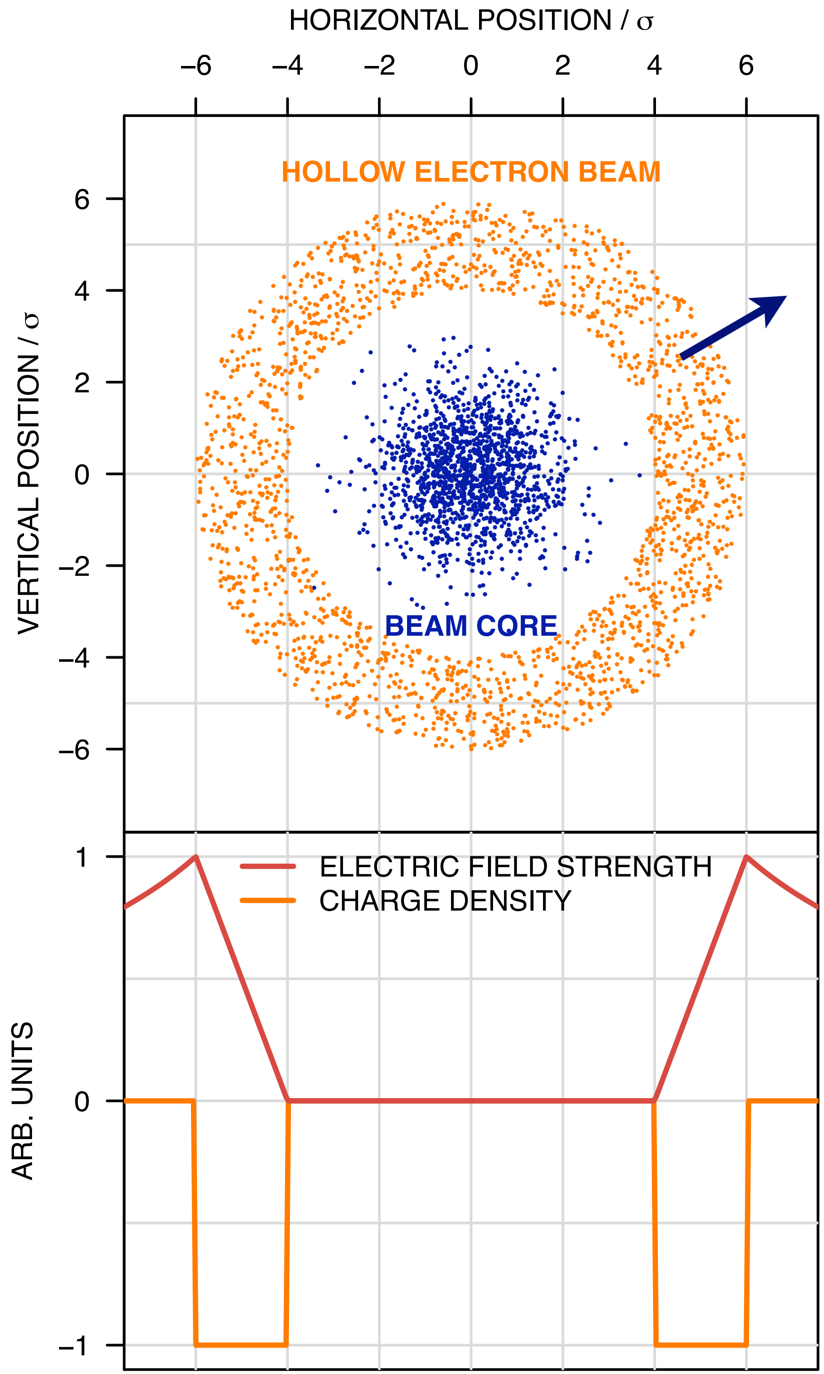
Thanks to AD Operations, CDF and DZero for support and study time

All Experimenters Meeting, February 21, 2011



Concept of hollow electron beam collimator (HEBC)



Halo experiences nonlinear transverse kicks:

$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

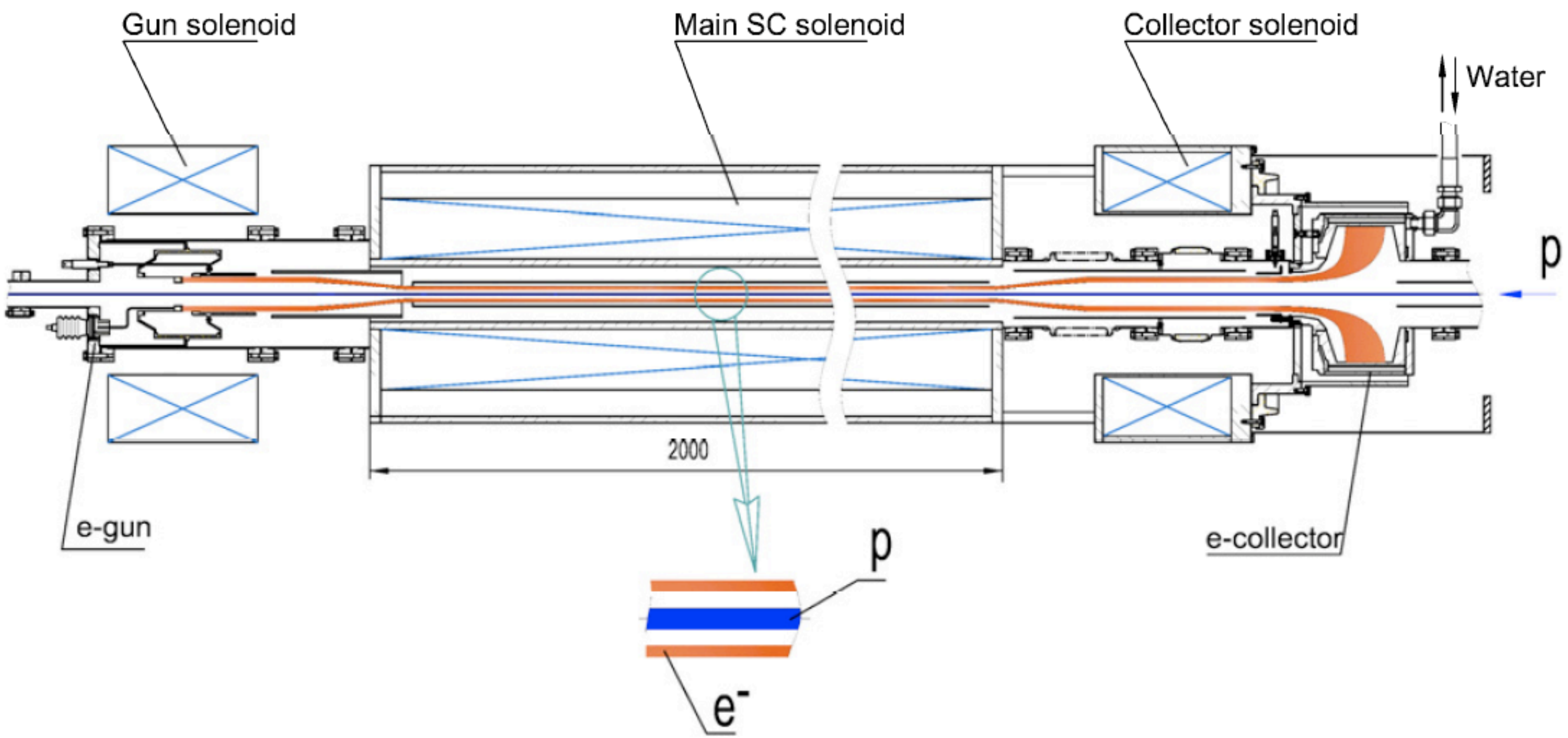
About **0.2 μrad** in TEL2 at 980 GeV

For comparison: multiple scattering in Tevatron collimators $\theta_{\mathrm{rms}} = 17\ \mu\mathrm{rad}$

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

Concept of hollow electron beam collimator (HEBC)

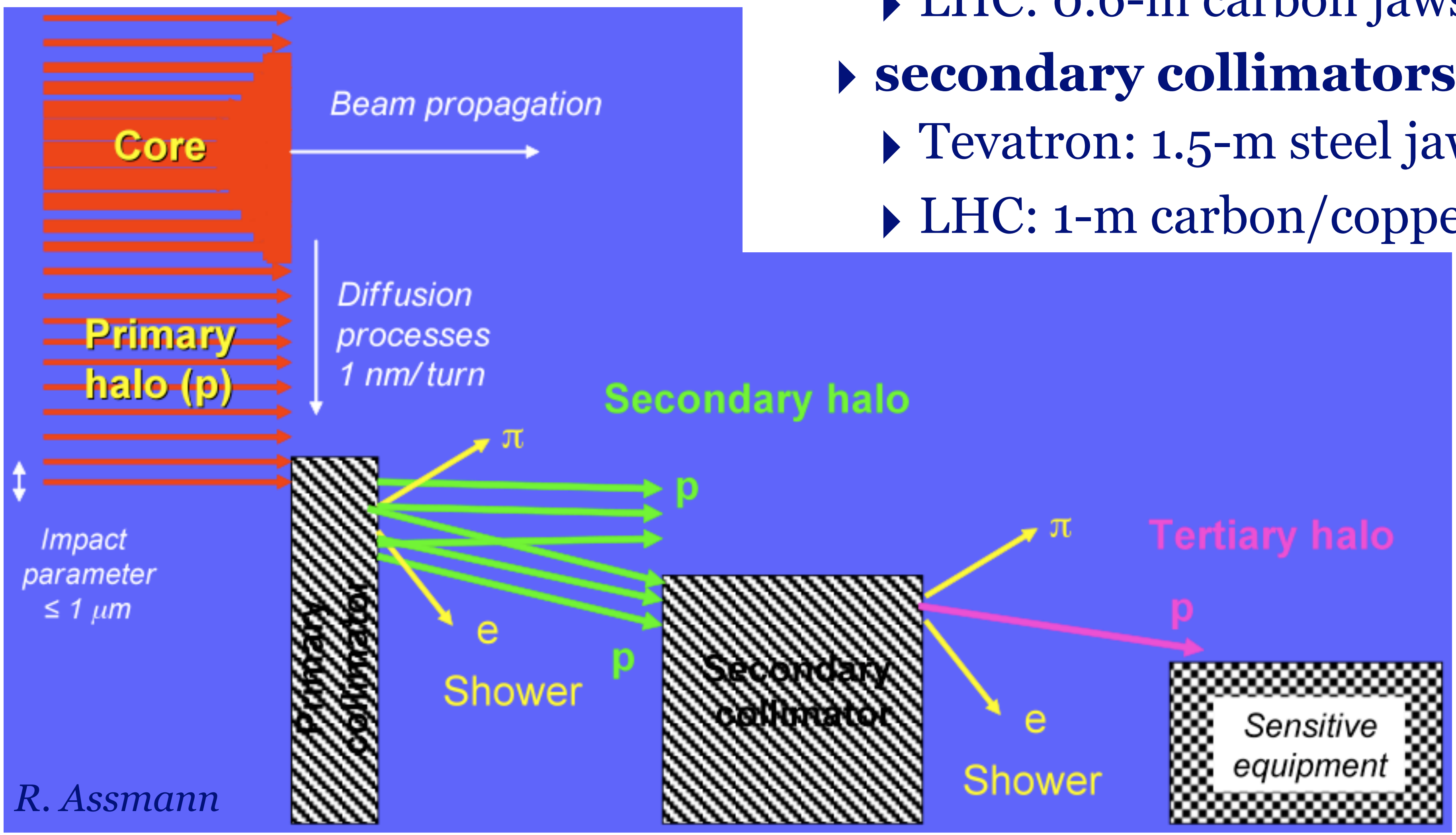
Cylindrical, hollow, magnetically confined, pulsed **electron beam overlapping with halo** and **leaving core unperturbed**



Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

The conventional two-stage collimation system

- Goals of collimation:
  - reduce beam halo
  - direct losses towards absorbers
- Conventional schemes:
  - **primary collimators**
    - Tevatron: 5-mm W at 5σ
    - LHC: 0.6-m carbon jaws at 6σ
  - **secondary collimators**
    - Tevatron: 1.5-m steel jaws at 6σ
    - LHC: 1-m carbon/copper at 7σ



A good complement to a two-stage system for high intensities?

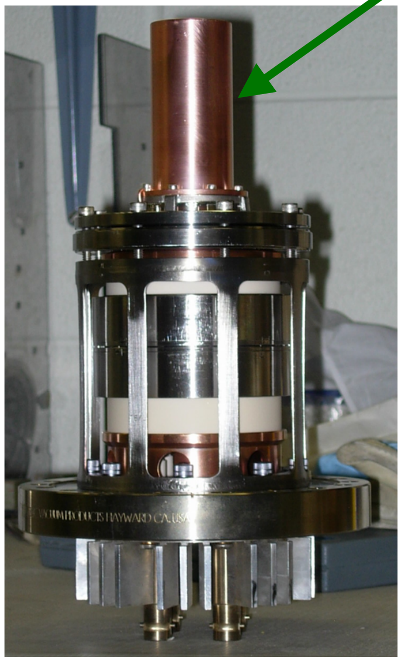
- Can be close to or even overlap with the main beam
  - no material damage
  - continuously variable strength (“variable thickness”)
- Works as “soft scraper” by enhancing diffusion
- Low impedance
- Resonant excitation is possible (pulsed e-beam)
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established e-cooling / e-lens technology
- Critical beam alignment
- Control of hollow beam profile
- Beam stability at high intensity
- Cost

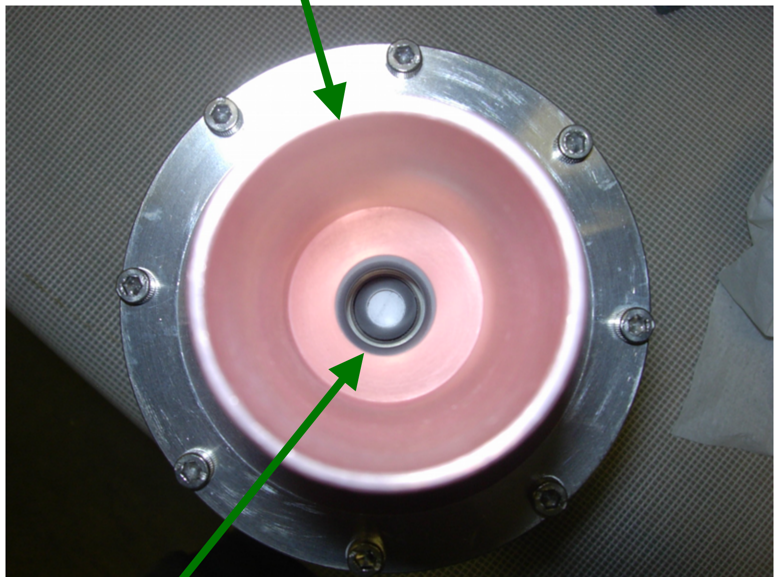
The 15-mm hollow electron gun

side view

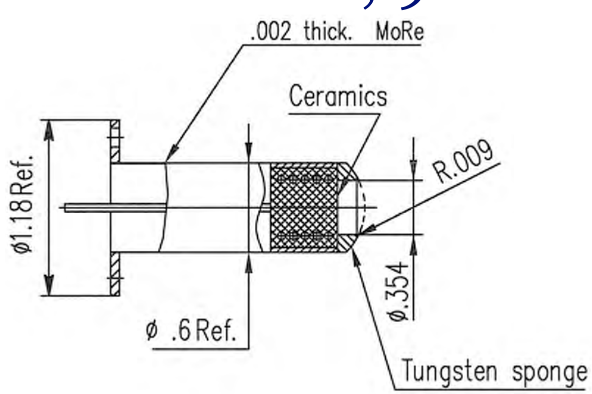
Copper anode

top view



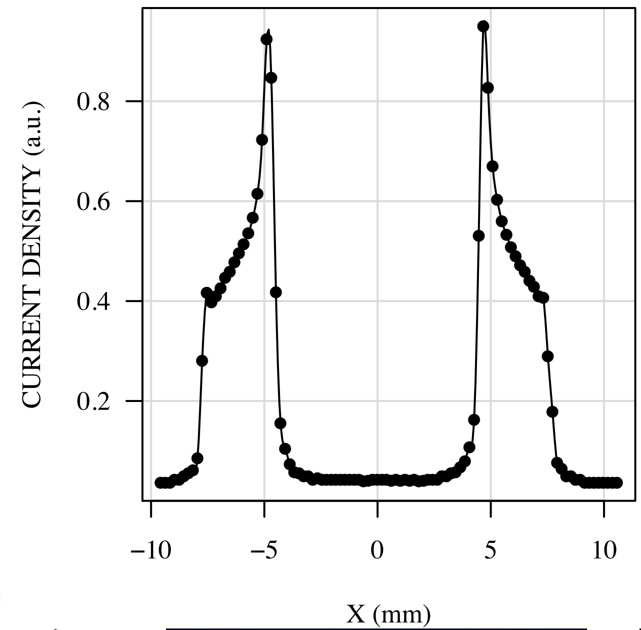


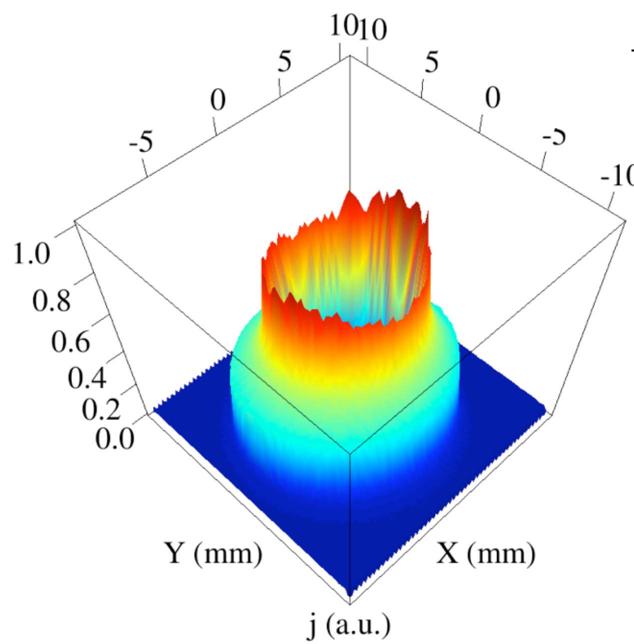
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

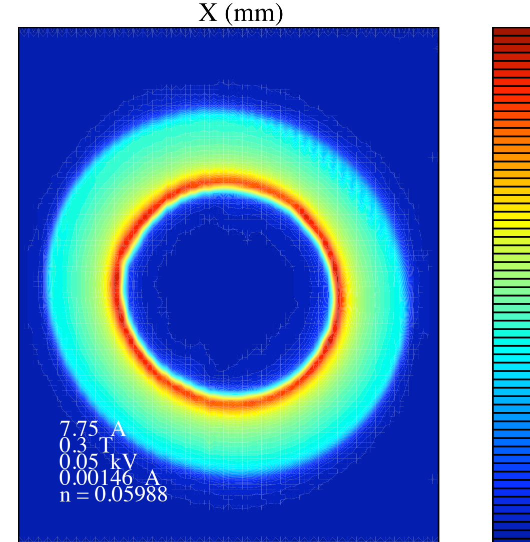


Yield: **1.1 A** at 4.8 kV

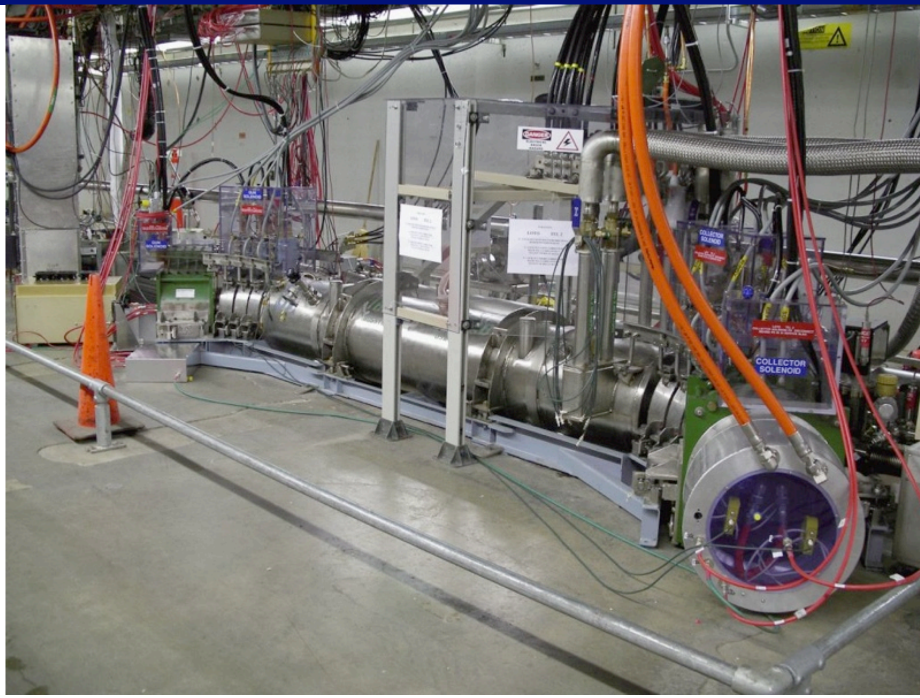
Profile measurements



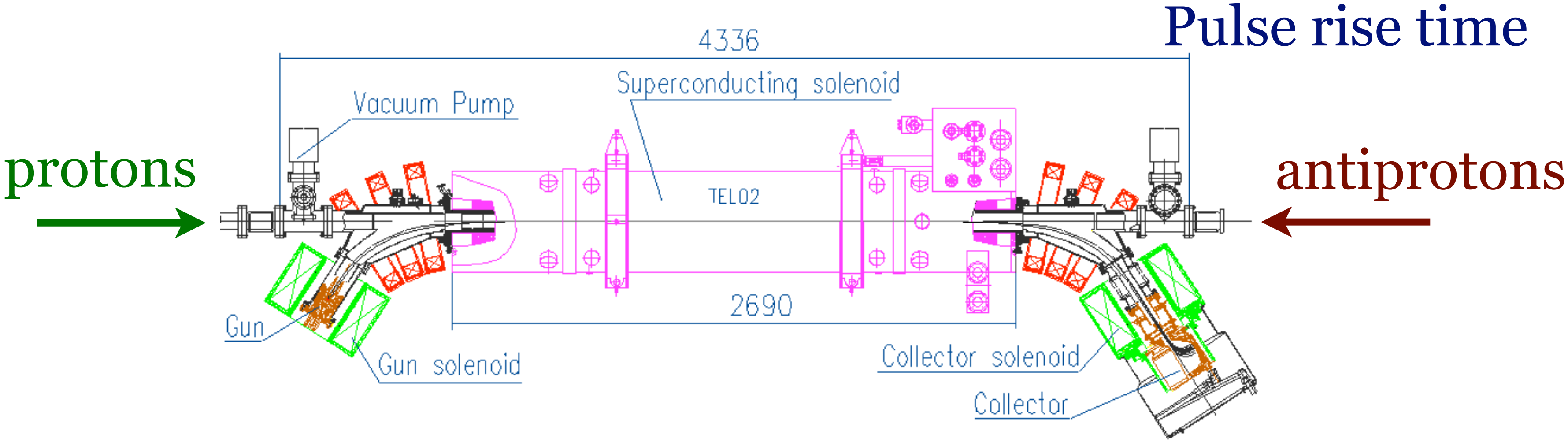




Installation in existing Tevatron electron lens (TEL2)

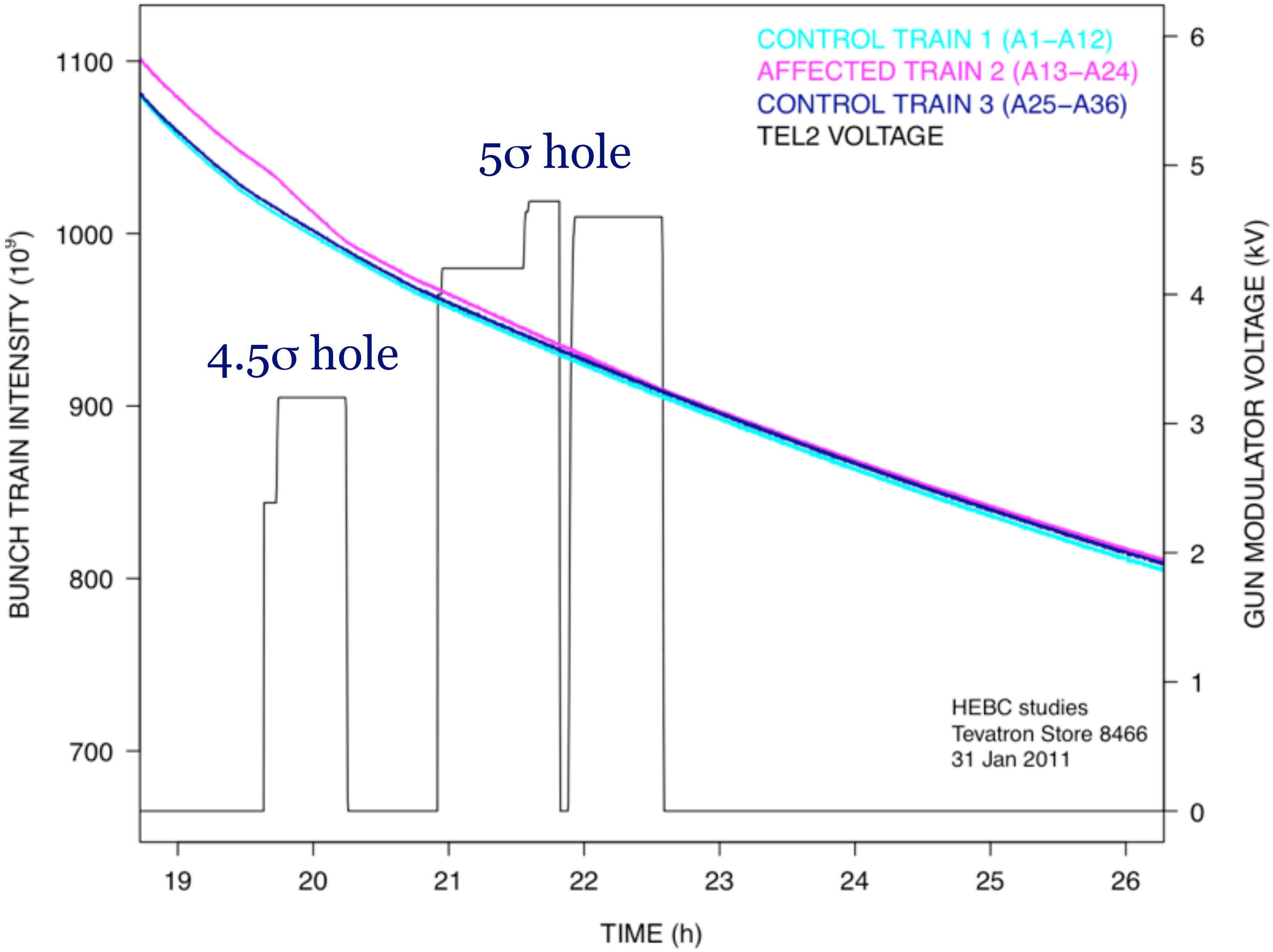


TEL parameters	
Peak energy	10 keV
Peak current	3 A
Max gun field	0.4 T
Max main field	6.5 T
Length	2 m
Rep. period	7 μs
Pulse rise time	200 ns

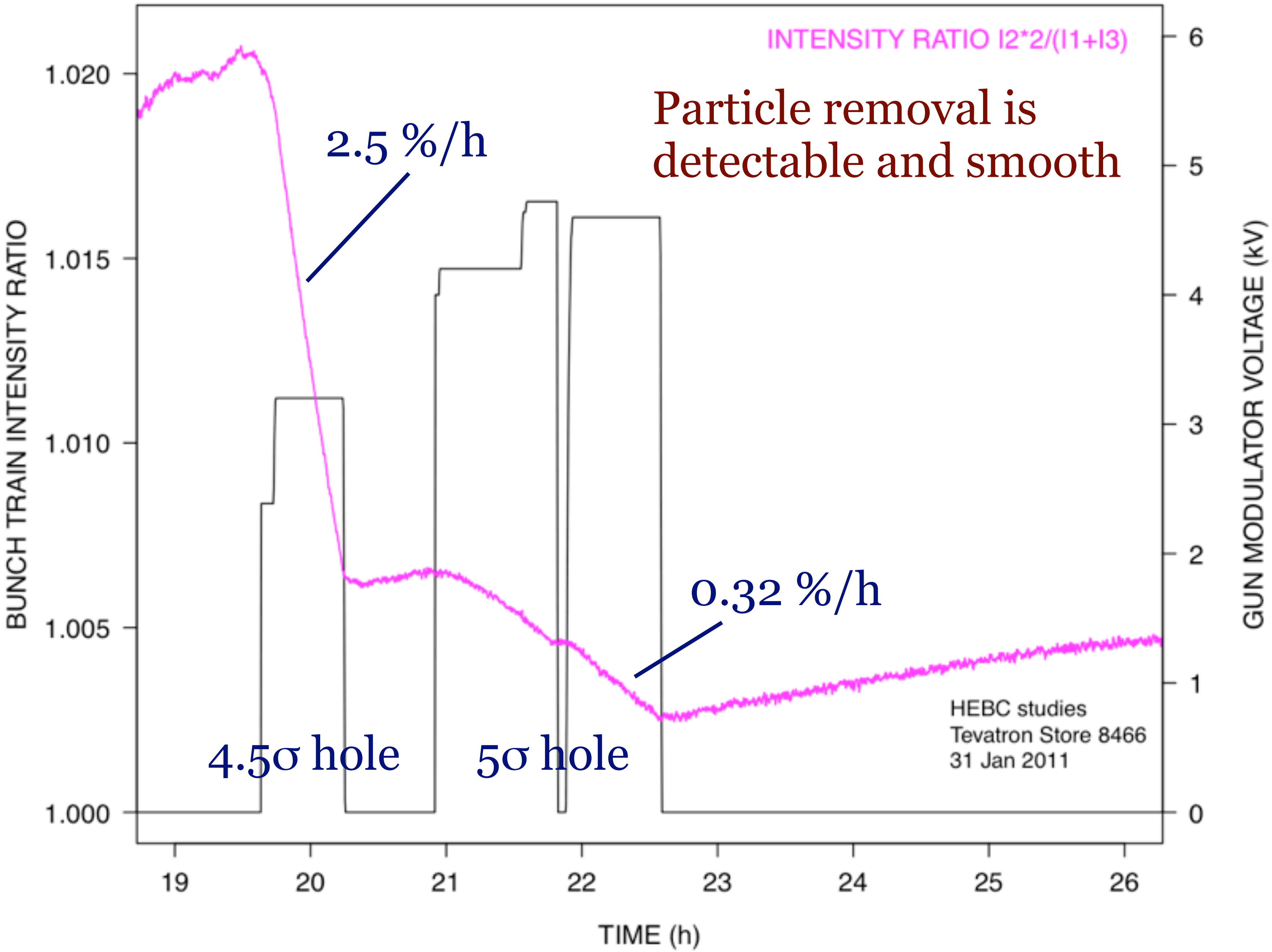


- TEL1 used for abort-gap clearing during normal operations
- TEL2 used as TEL1 backup and for studies

HEBC acting on 1 antiproton bunch train (A13-A24)



Removal rate: affected bunch train relative to other 2 trains



Is the core affected? Are particles removed from the halo?

Three strategies:

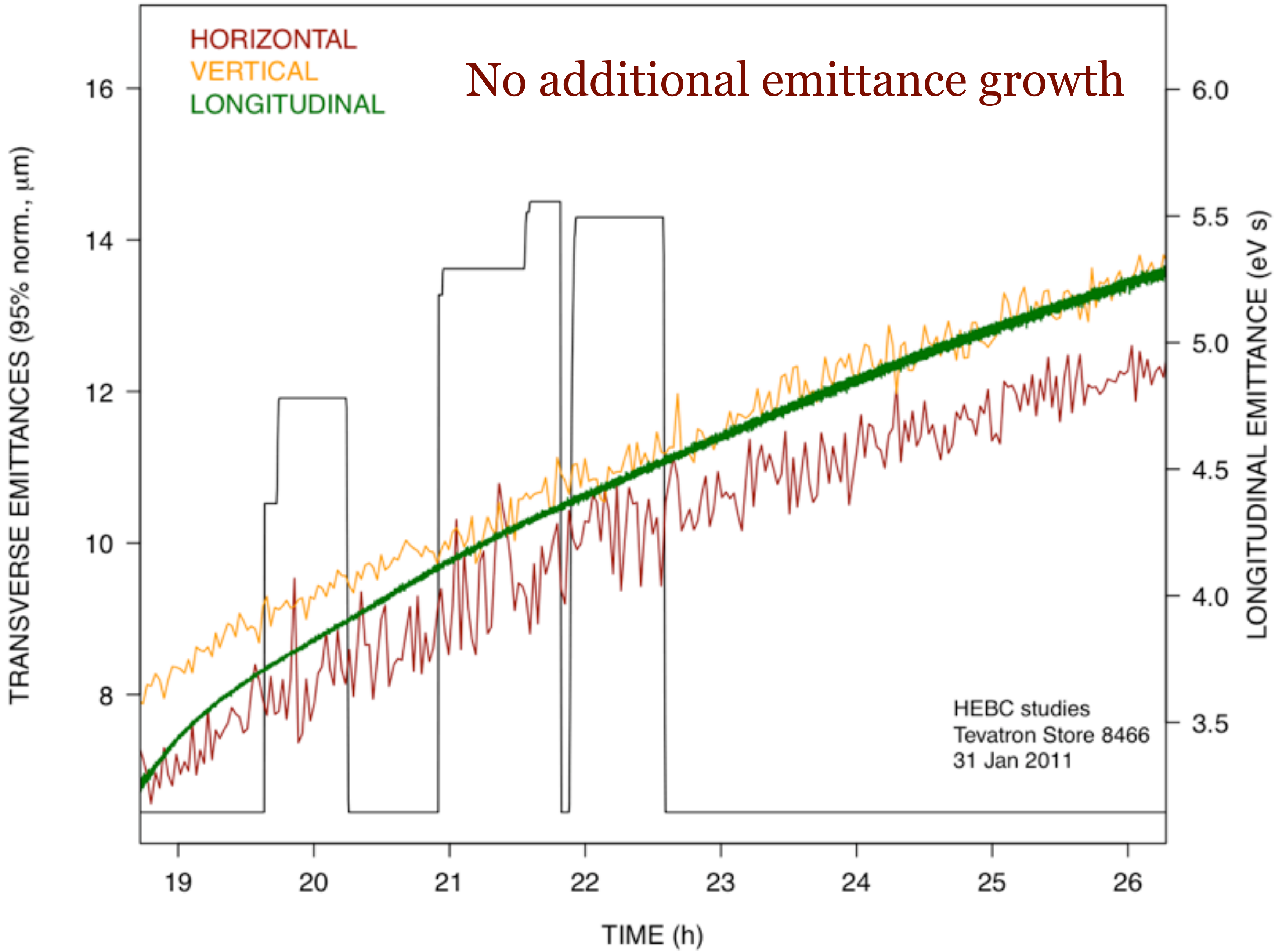
- Check **emittance** evolution
- Compare **intensity** and **luminosity** variations when removing antiprotons:

$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2\frac{\Delta\sigma}{\sigma}$$

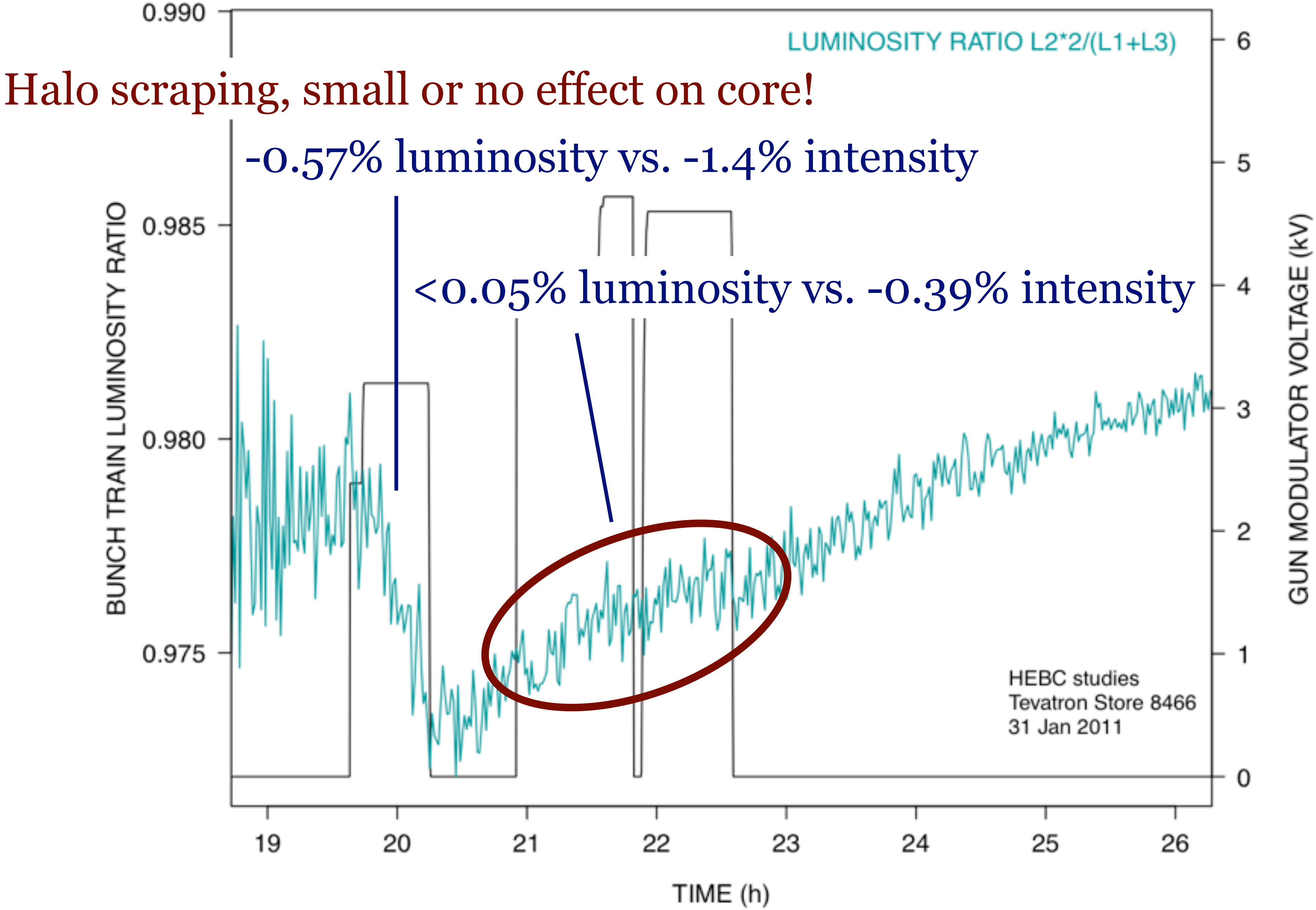
  - <u>same fractional variation</u> if other factors are constant
  - luminosity decreases <u>more</u> if there is emittance growth or proton loss
  - luminosity decreases <u>less</u> if removing halo particles (they do not contribute to the luminosity measurement)

- Estimate **halo population** and **diffusion** rates directly with **collimator scans**

Emittances of affected bunch train



Luminosity of affected bunch train relative to other 2 trains

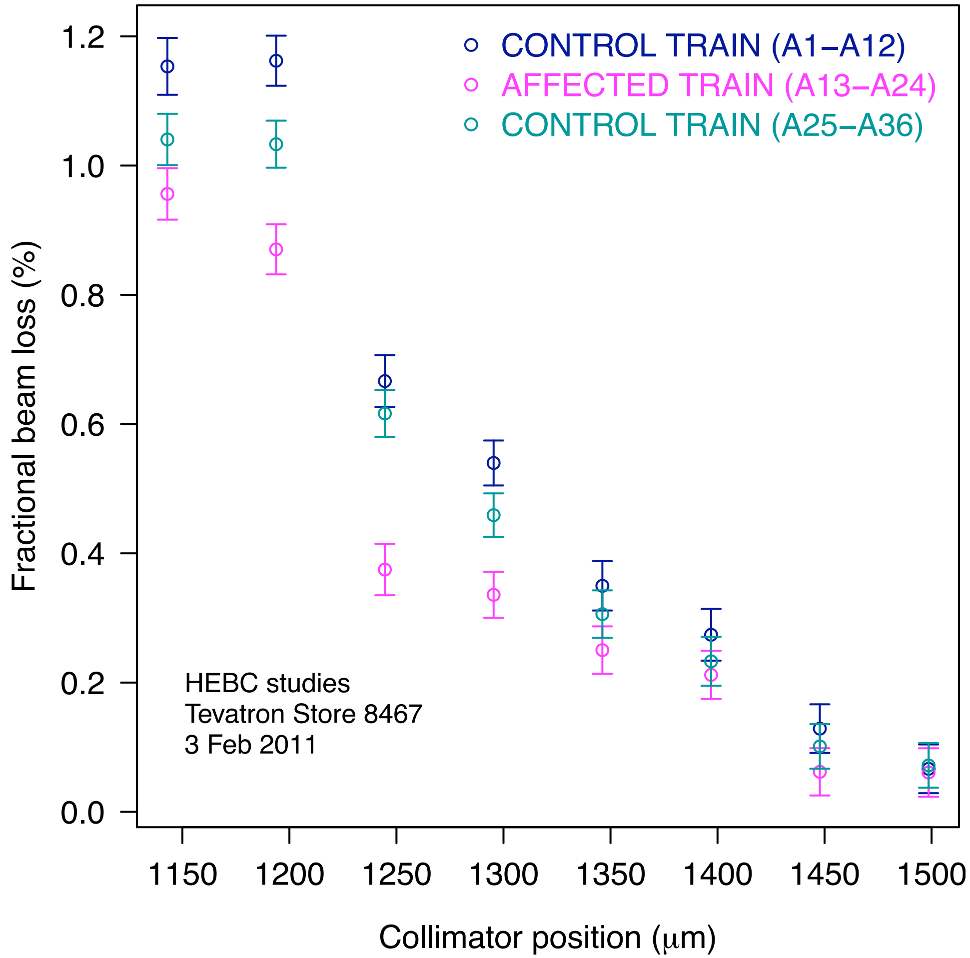


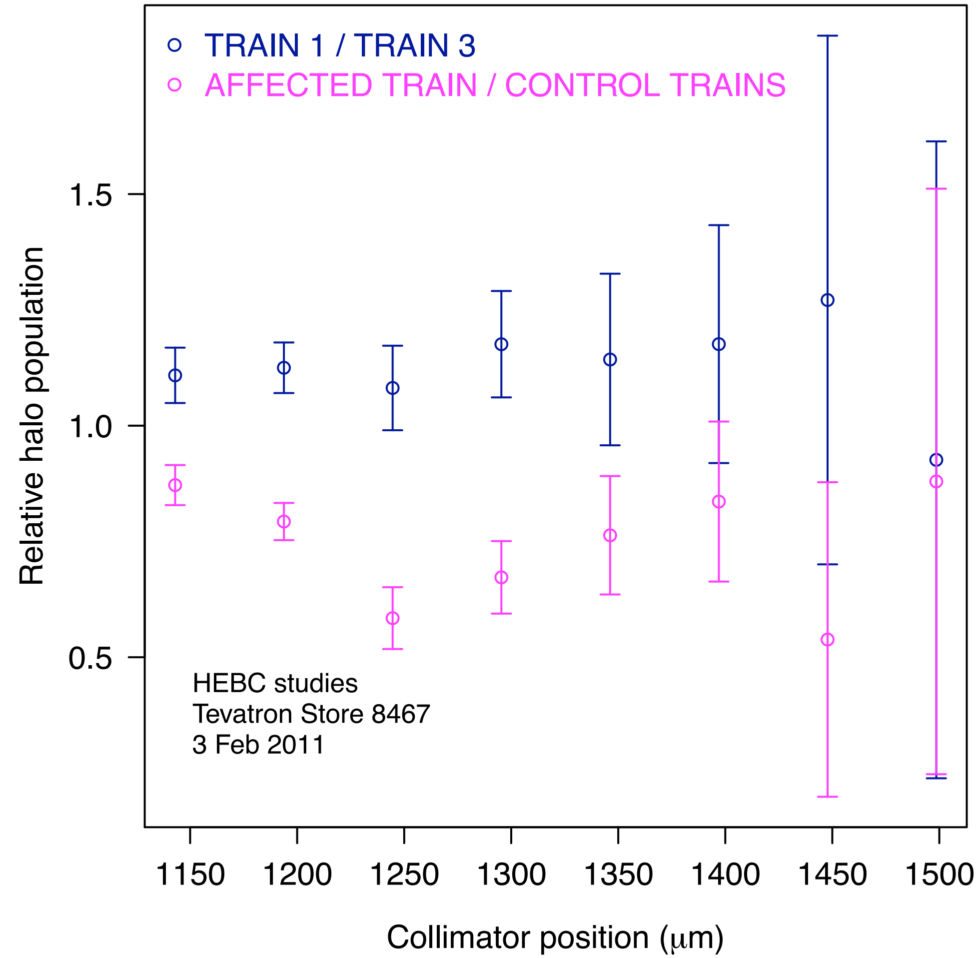
Halo populations from collimator scan - preliminary

HEBC on second antiproton train, 3.5σ hole (1.3 mm at collimator)

Vertical collimator scan

HEBC scraped only 1% of total intensity, but tails were reduced by up to 40%





down towards beam center

Conclusions

- Prototype hollow gun installed in the Tevatron (TEL2) in Aug 2010
- Studies started in Oct 2010
- Alignment is reproducible
- With aligned beams, no instabilities or emittance growth
- Studies are mostly parasitical
- Observed scraping effect of hollow electron beam collimator
- Observed differential halo/core scraping and reduction of tails
- Next studies: diffusion, efficiency, protons
- Design of 25-mm cathode (higher current, larger hole for protons)
- New guest scientist joined group to work on modeling
- Collaboration with LHC Collimation Group; project is partially supported by U.S. LARP

Thanks for your attention

Backup slides

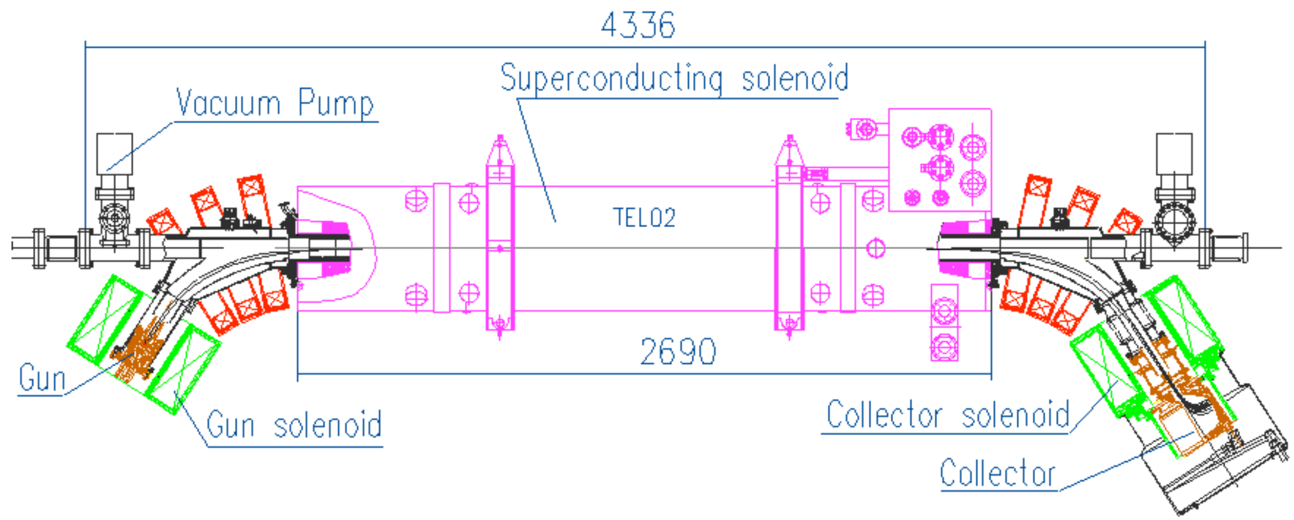
Brief project history

- **Summer ’09**
  - Hollow gun design (Kuznetsov, Vorobiev)
  - TEL2 BPM software upgrade (Romanov/BINP)
- **Aug ’09**: Hollow gun manufactured and delivered (Hi-Tech Mfg)
- **Fall/winter ’09**:
  - Hollow beam dynamics studies in test stand (Valishev, gs)
  - TEL2 BPM calibrations (Valishev, gs)
- **August ’10**:
  - Hollow gun installed in TEL2 (Kuznetsov, Sylejmani, gs)
  - Complete system test (Saewert, Simmons, Crisp, Fellenz, Kuznetsov, Zhang, gs)
  - Verified abort-gap clearing as TEL1 backup (Zhang)
- **October ’10**: First Tevatron experiments (Valishev, gs)

Modeling and simulations

kick maps in overlap region → **tracking software** with lattice/apertures

- analytical form, ideal case
- 2D from measured profiles
- 3D particle-in-cell
  - TEL2 bends
  - profile evolution
  - misalignments

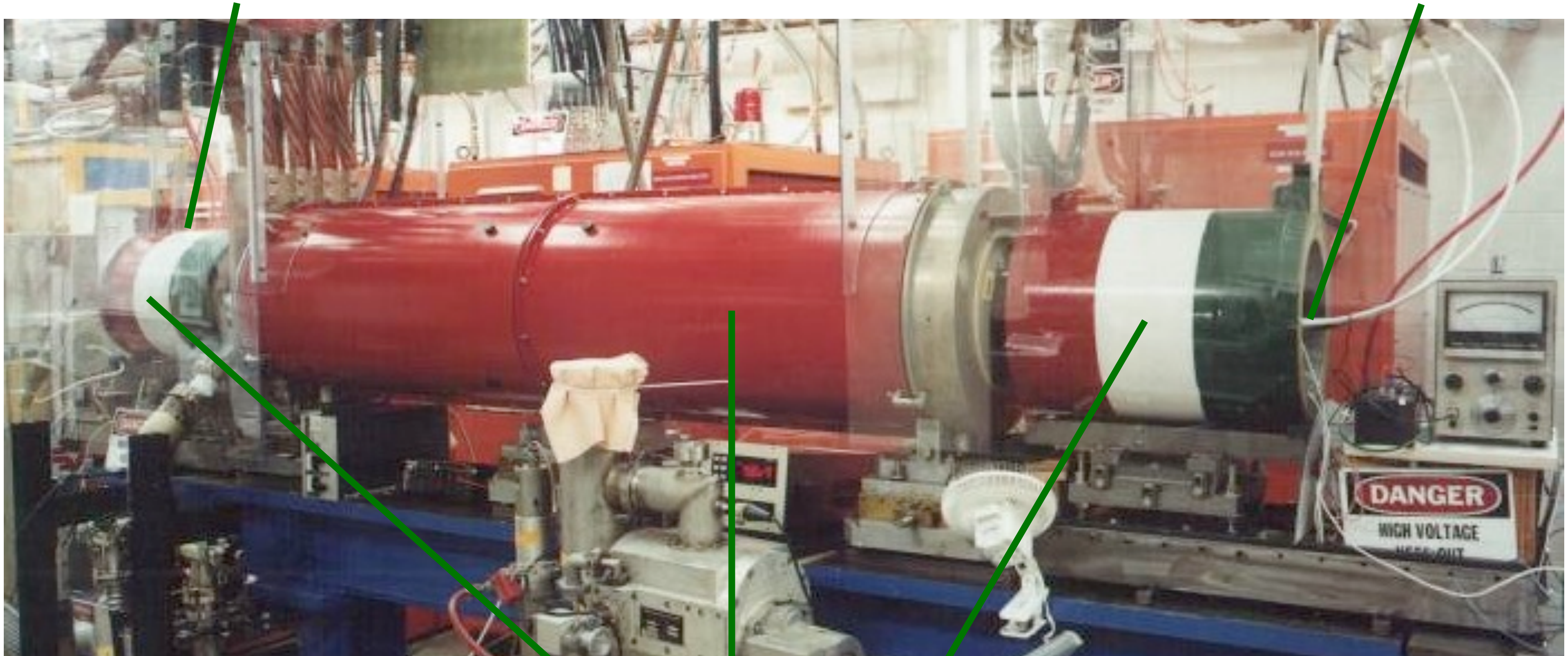


- Tevatron: `STRUCT` (Drozhdin), `Lifetrac` (Valishev)
- LHC: `SixTrack` (Smith/SLAC → Bruce/CERN)
- hollow e-beam dynamics: analytical/`xpdp2`/`Warp` (Chung, gs)
- I. Morozov (guest scientist) joining Jan ’11 for 1 year

Fermilab electron-lens test bench (lower linac gallery)

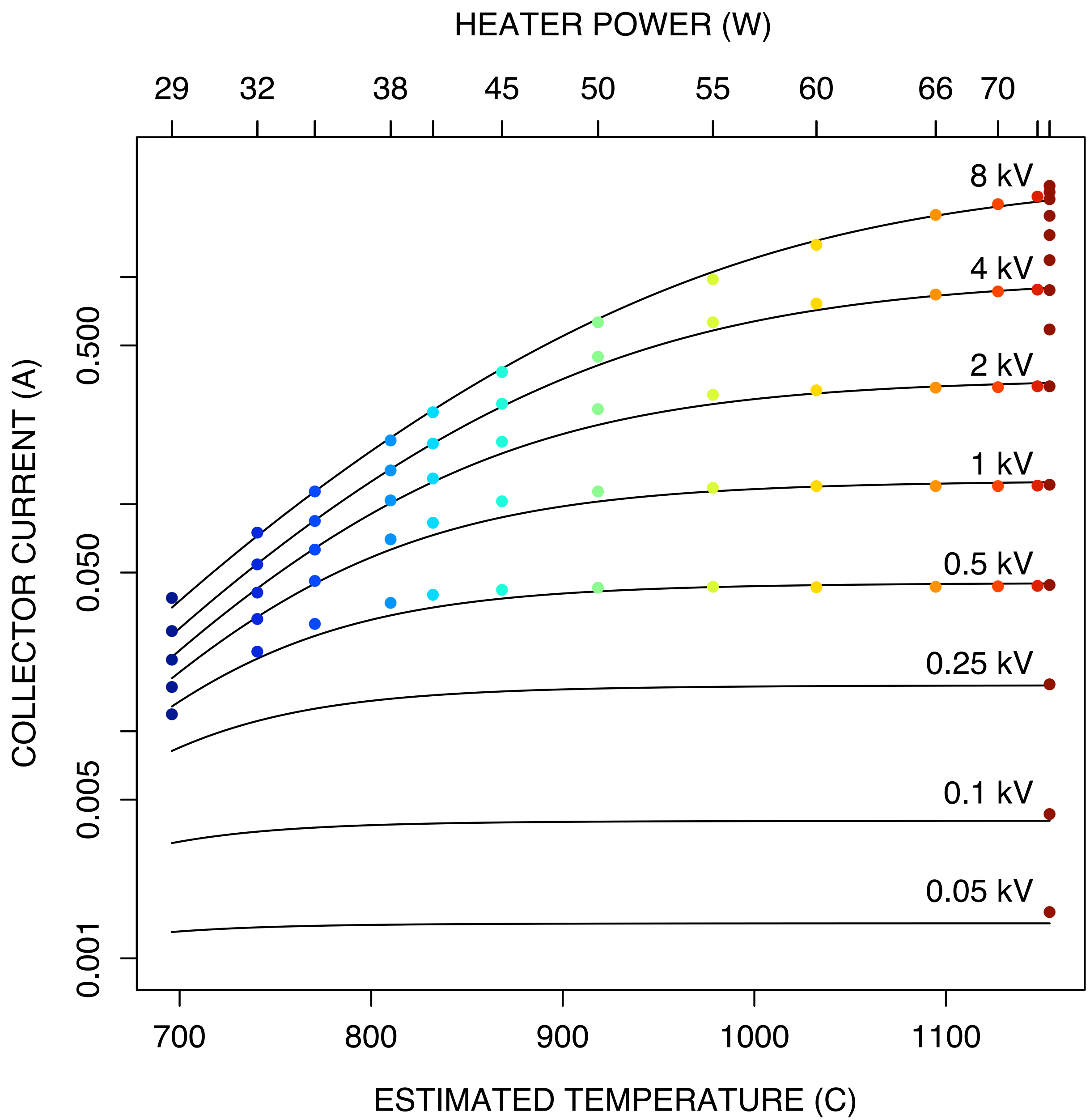
High-perveance **electron guns**:
peak current ~4 A @ 10 kV
pulse width ~ μs

Water-cooled **collector**
with 0.2-mm pinhole for
profile measurements



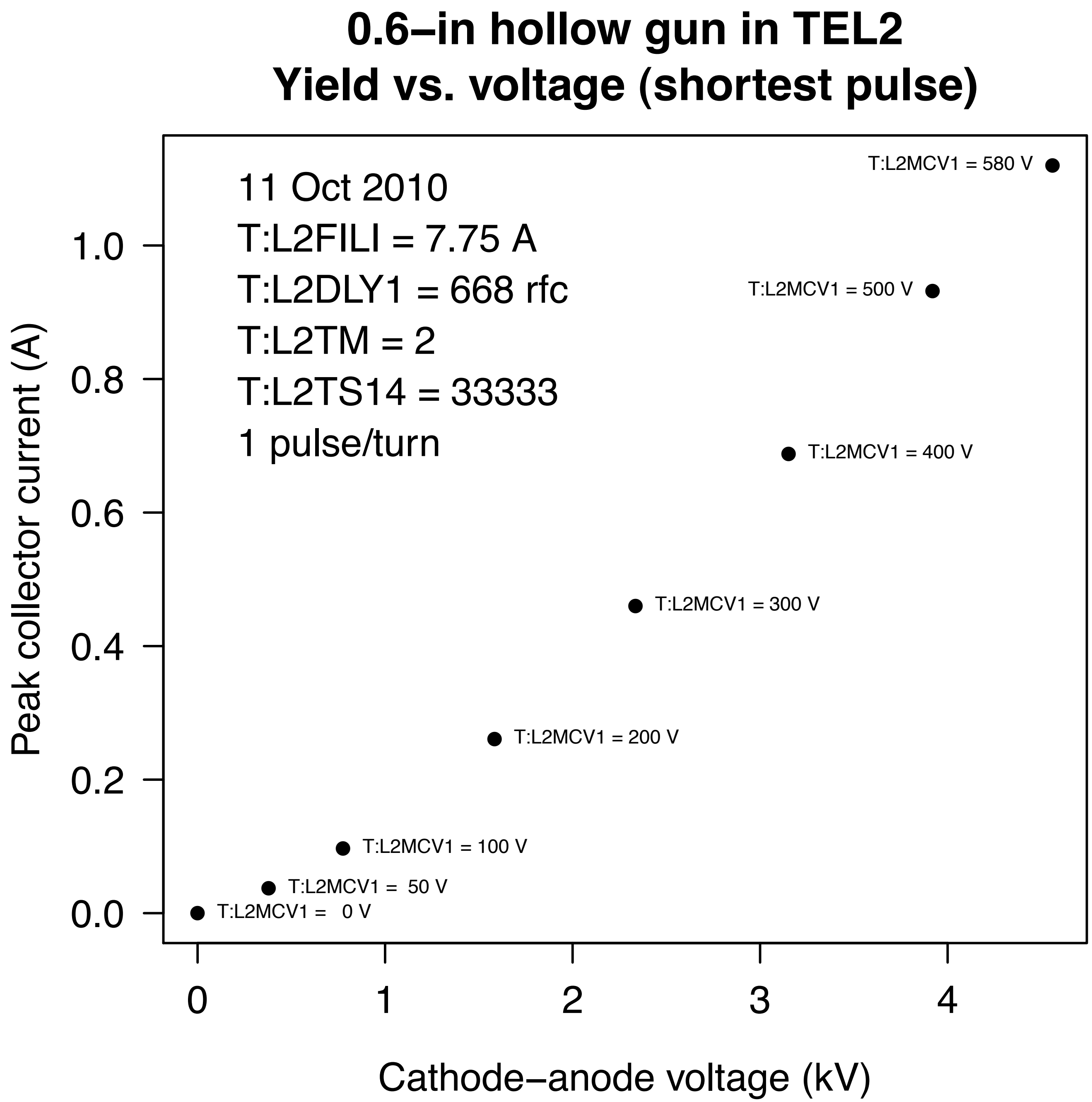
Gun/main/collector
solenoids < 0.4 T
magnetic correctors
pickup electrodes

Performance of hollow cathode vs. voltage and temperature

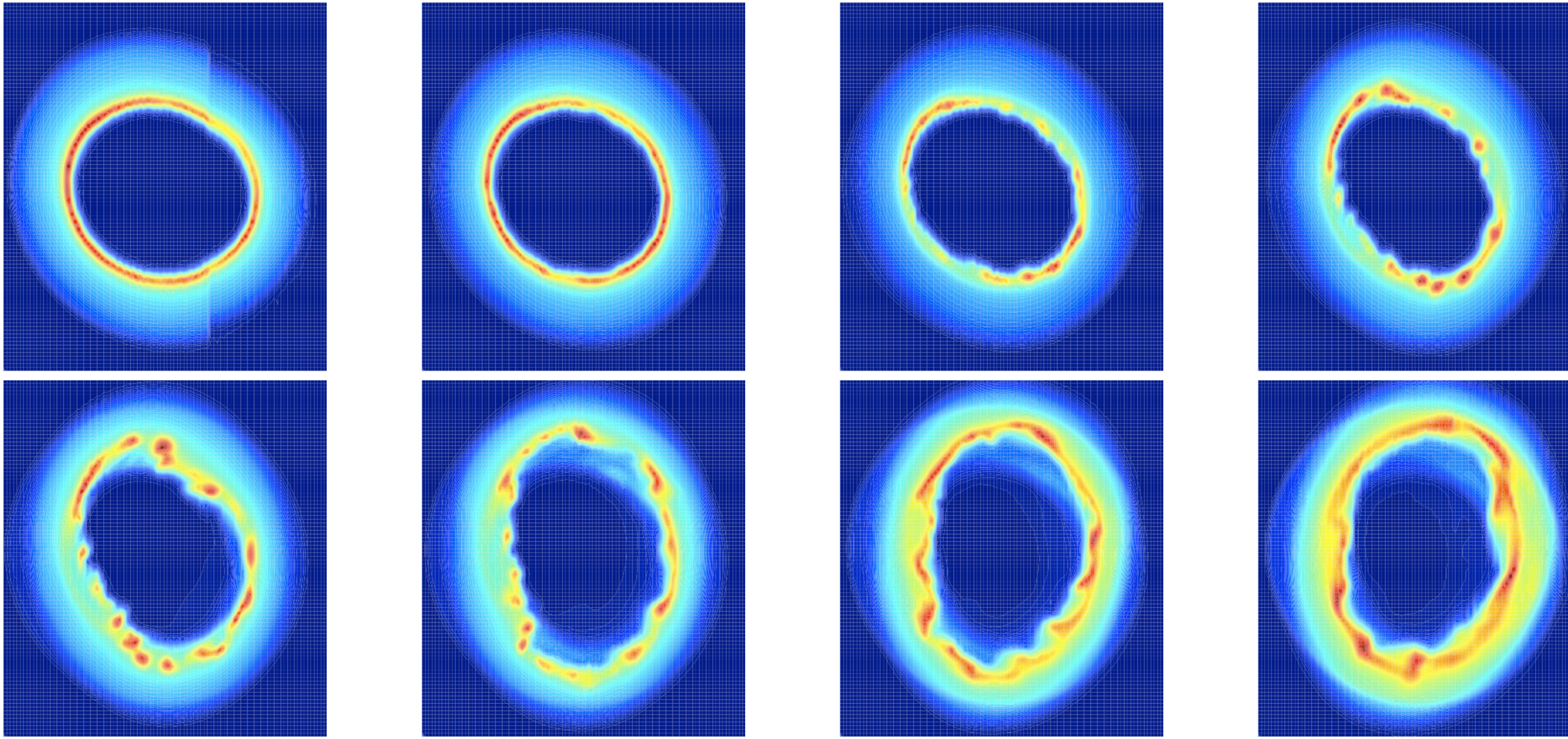


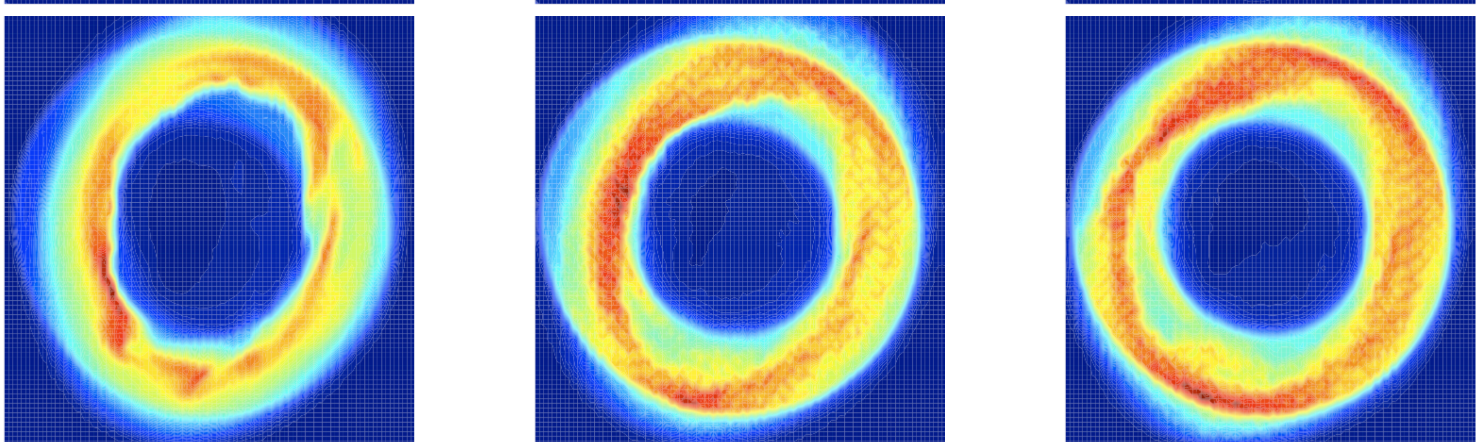
temperature limited ⟶ space-charge limited $I \propto V^{3/2}$

Hollow gun performance in TEL2 after cathode conditioning



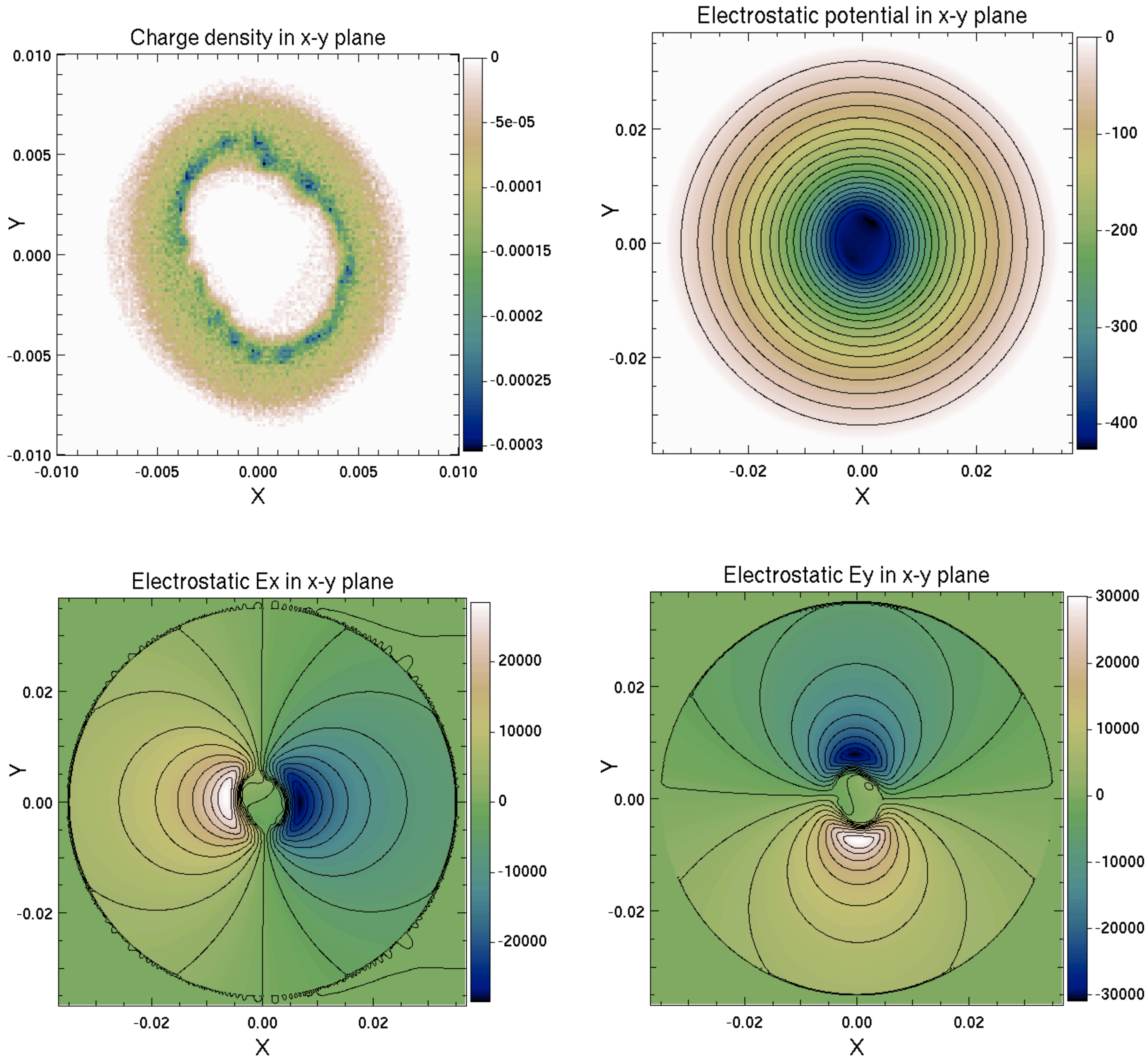
Measured profile evolution with current and voltage at 3 kG





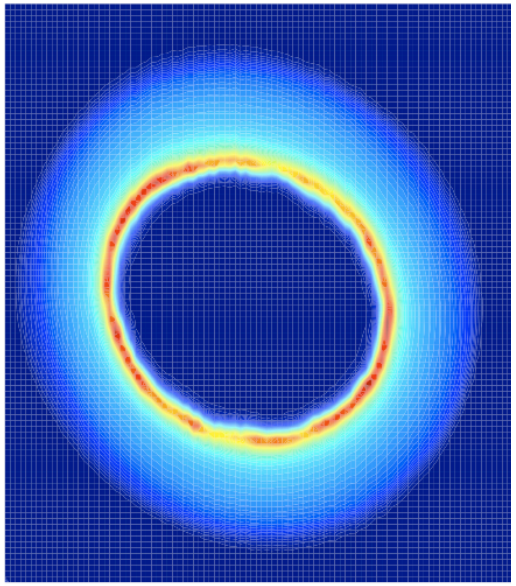
Example of nonneutral plasma slipping-stream ('diocotron') instability

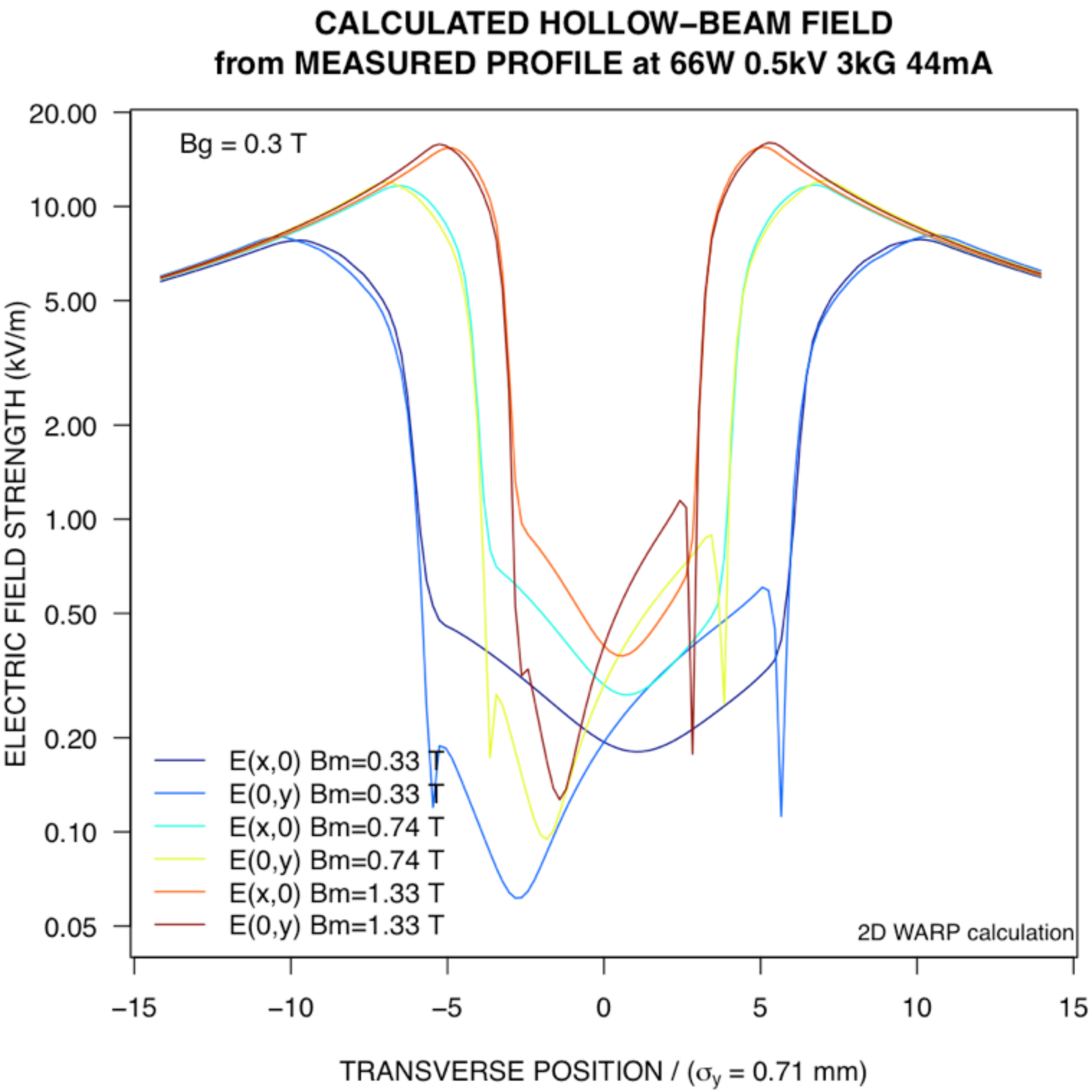
Warp calculation of 2D fields from measured profiles



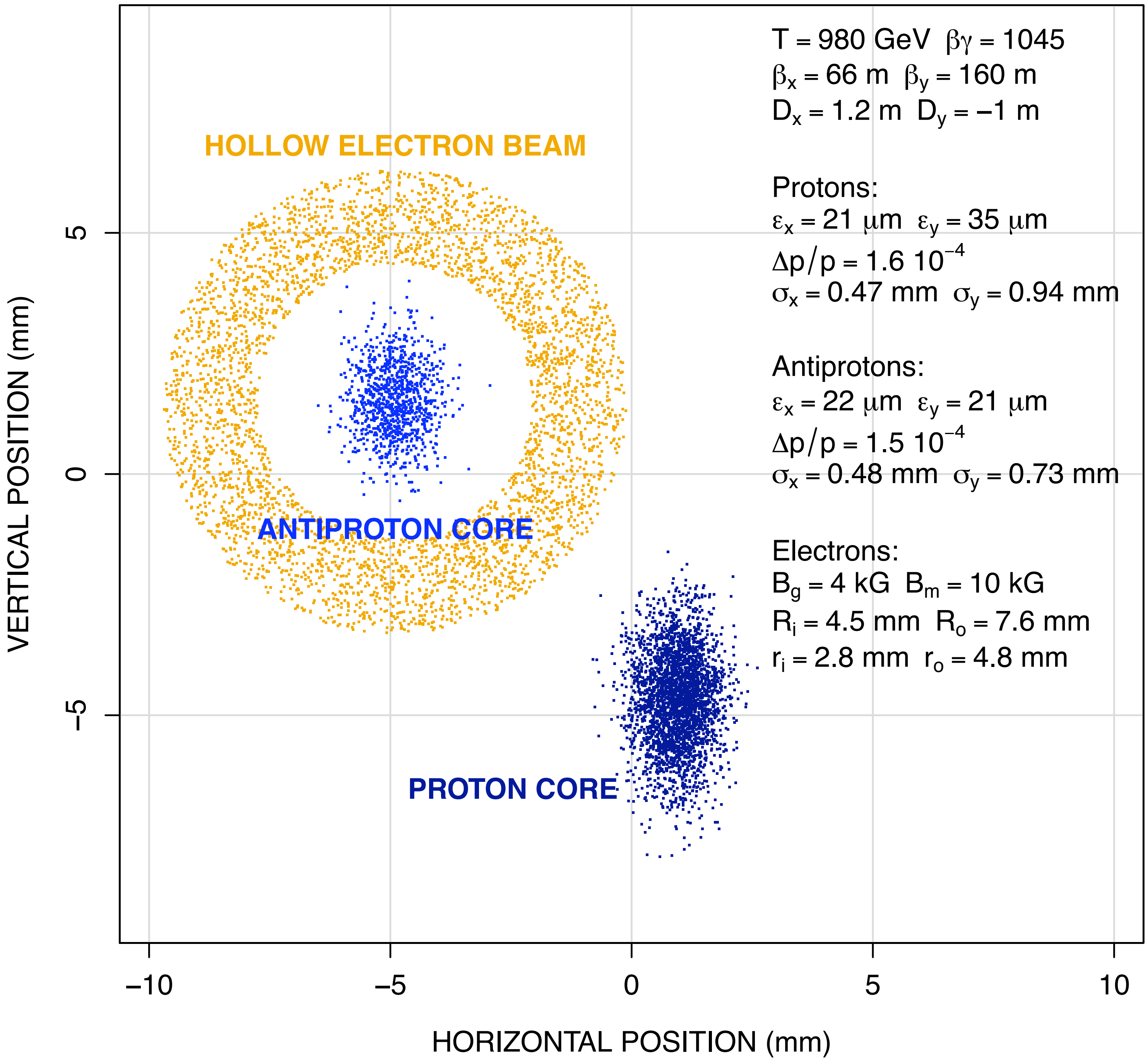
thanks to D. Grote, J.-L. Vay, M. Venturini (LBL) for kind support

Electric fields at 0.5 kV, 44 mA





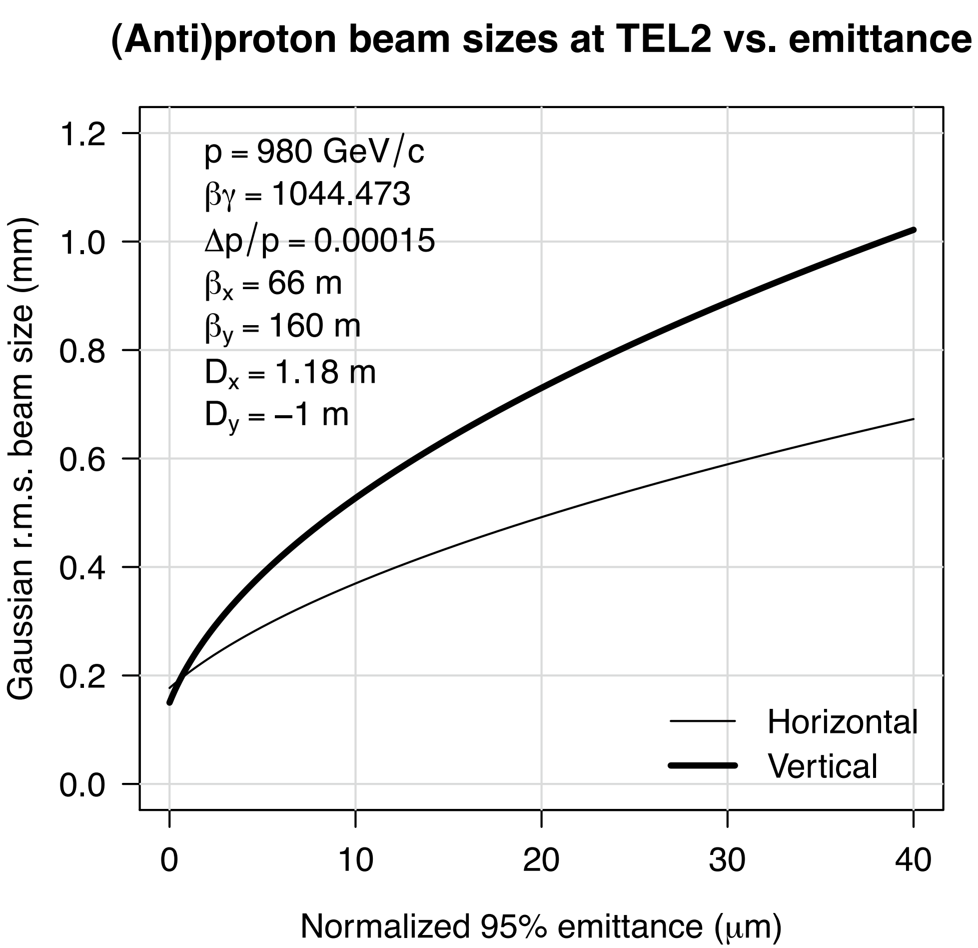
Example of transverse beam profiles at TEL2

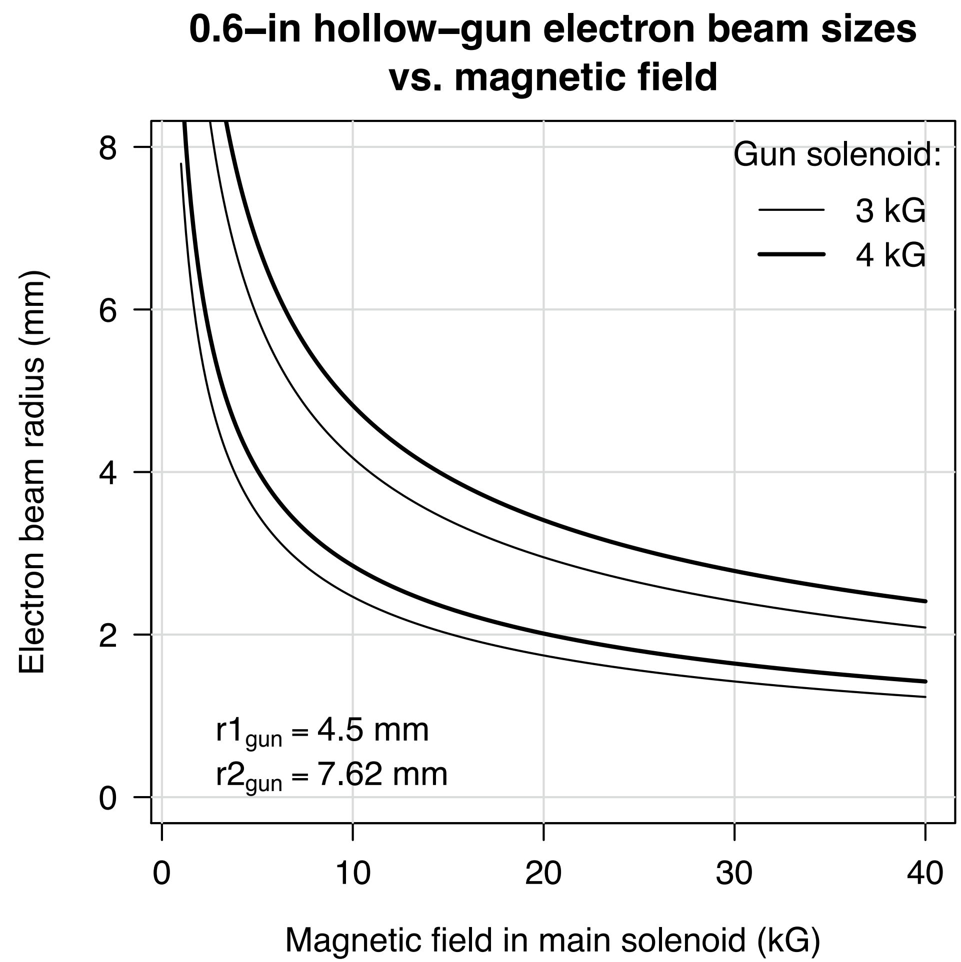


Collimation of antiprotons

We chose to start with antiproton bunches:

- lower emittances and intensities, larger magnetic field ⇒ more stable
- in Tev lattice, TEL2 more similar to pbar collimator ⇒ better capture





e-beam pulse synchronization with antiproton bunch